Spaceborne Passive Microwave Measurement of Snowfall over Land

Min-Jeong Kim
Department of Atmospheric Sciences, University of Washington, Box 351640, Seattle, WA 98195
206-685-1851, FAX 206-543-0308, mjkim@atmos.washington.edu

G. Skofronick-Jackson
NASA Goddard Space Flight Center, Code 975, Greenbelt, MD 20771

J.A.Weinman
Department of Atmospheric Sciences, University of Washington, Box 351640, Seattle, WA 98195

Dong-Eon Chang
Forecast Research Laboratory, Meteorological Research Institute, Seoul, 156-720, Korea

Abstracts

A physically based retrieval algorithm was developed to estimate snowfall over land. The retrieval algorithm relies on the MM5 model that generates the vertical structure of a snow cloud, including snow mass, snow particle effective diameter, and water vapor. The MM5 cloud simulation was used to provide statistics for generating the cloud characteristics. The snow cloud profile and surface emissivity were then used in radiative transfer calculations that were optimized against AMSU-B observations at 89, 150 and 183.3±7, ±3, and ±1 GHz. The multi-parameter cloud model that produced brightness temperatures that best fit the AMSU-B observations was selected as the retrieved profile. The retrieved snowfall distribution was validated with radar reflectivity measurements obtained from the operational NWS radar network.

1. Introduction

Measurement of global precipitation is one of the goals of climate studies. Although most global precipitation occurs as rainfall, snowfall plays a significant role in the extra-tropical hydrological cycle. One important challenge for future satellites is to detect these snowstorms from space.

Because snow accumulation on land affects the emission properties of the surface, measurement of snowfall within the atmosphere has been difficult with radiometers that operate at frequencies where the atmosphere is relatively transparent. However, water vapor absorption at frequencies greater than 100 GHz can screen the emission from snow covered surfaces. The Special Sensor Microwave/T-2 (SSM/T-2) radiometer, and the Advanced Microwave Sounding Units (AMSU-B) radiometers on the NOAA 15,16, and 17 spacecraft, provide observations at 89, 150 and 183 ±1, ±3, ±7 GHz. Snowfall over land has been empirically derived from the brightness temperatures at frequencies where water vapor absorption occurs by [1] and [2]. Although such empirical relationships are operationally useful, physical models, on which this study is focused, are needed to understand how the retrieved snowfall depends on the various ground-atmosphere factors that affect the measured brightness temperatures. This study presents a physical model of radiation at millimeter-wave frequencies that seeks to infer snowfall rates over land by taking advantage of water vapor screening to obscure the underlying snow-covered surface.

2. Case Study

This study retrieved snowfall for the March 5-6, 2001 New England blizzard that deposited 75 cm of snow in Burlington, VT, USA. Since the mean temperatures encountered in NH and VT remained around –5 C, and reported maxima were only –2 C, we disregarded melting over inland regions.

Fig. 1 shows a composite of the National Weather Service (NWS) operational weather radar reflectivity, Z_{eff} (mm^6/m^3) obtained on March 5, 2001 at 23:00 UTC. The snowfall was greatest over CT, MA, VT and NH. The maximum reflectivity in the smoothed radar reflectivity data is ~37 dBZ at a 16 km x 16 km resolution, which is the finest spatial resolutions of the AMSU-B channels.

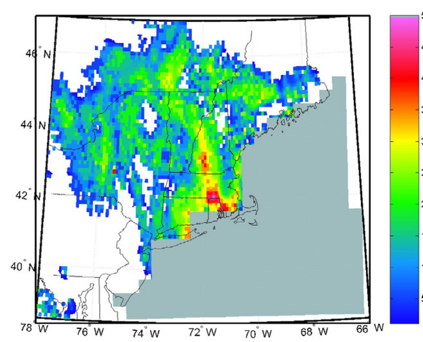


Fig.1 Radar reflectivity (dBZ) obtained from the NWS operational radar composite at variable heights between 0.5 amd 2.5 km measured at 23:00 UTC on March 5, 2001. The ocean was hidedin grey.

Fig. 2 shows the distributions of the 89 and 183.3 ± 7GHz brightness temperatures measured from AMSU-B at 23:02 UTC on March 5, 2001. The cold Tb_{89} values scattered over Canada may have been caused by accumulated antecedent snow, Fig.2(a). It is difficult to distinguish snow in the atmosphere from snow on the ground at this window frequency. However, the Great Lakes and the St. Lawrence River, that are evident in Fig. 2(a), are screened by water vapor in the lower atmosphere as shown in Figs. 2(b).

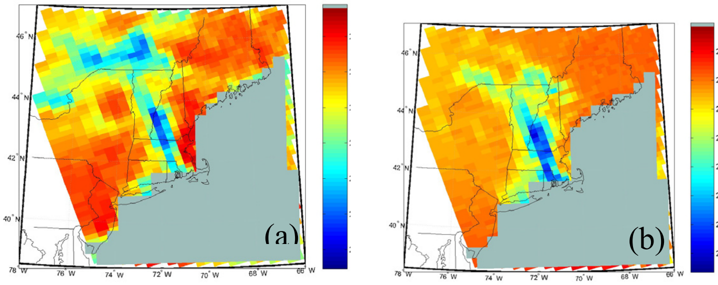


Fig.2 Brightness temperatures observed from the (a) 89 GHz and (b) 183.3±7 GHz channels of AMSU-B observed at 23:02 UTC on March 5, 2001.

3. Snowfall Retrieval Methodology

3.1 Three Variable Parameters[1,2,3]

This study seeks to derive characteristics of snow whose electromagnetic properties are consistent with microwave brightness temperatures at several frequencies provided by the AMSU-B sensors. Brightness temperatures are computed from an Eddington approximation of the second kind. The radiative transfer model employs information from the Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) fifth-generation Mesoscale Model (MM5). A more comprehensive description of the MM5 model applied to an earlier winter storm was presented by [3].

In addition to [1]*the fractional surface snow cover (***f***)* to adjust the surface emissivity, these MM5 profile distributions form the basis of parameters determining [2]*the relative hu*midity profile (**r**) and [3]*the snow mass profile (***M***)* used as input for forward radiative transfer calculations with an Eddington 2nd approximation with delta-scaling (Kim et al. 2003). These three parameters, along with assumption of the fixed temperature profile and snow size distribution, produce snow cloud characteristics used to generate brightness temperatures that would be observed at the AMSU-B frequencies using forward radiative transfer calculations. The optimal estimate of the snow parameters is derived from the best match between computed and measured brightness temperatures at *all* AMSU-B frequencies.

3.2 Snow Size Parameter Selection

The greatest challenge of this study is determining the electromagnetic properties of the wide variety of shapes and sizes of snowflakes. Since the mean temperatures encountered in NH and VT on 5 March 2001 hovered around –5 C, and reported maximum temperatures were only –2 C, snow over NH and VT was regarded as dry containing no melt water. The microphysics characteristics defined by the MM5 model were found to be inadequate to account for the high frequency microwave scattering properties of snow. The low density (fluffy particles) assumed by the MM5 model did not provide enough scattering because the asymmetry factor was too large. Consequently scattering was insufficient to produce the cold observed brightness temperatures. The inappropriateness of applying effective medium mixing theories to irregularly shaped hydrometeors with size parameter of large structural inhomogeneities was cited by [4].

Although the finite difference time domain method can be used to compute the scattering characteristics of non-spherical particles, the shape of the frozen crystal habit can only be crudely estimated so that a simpler approach seemed justified.

One such simpler approach is the procedure of Grenfell and Warren [5]. The G-W procedure transforms randomly oriented inhomogeneous non-spherical (e.g., fluffy) ice particles into an ensemble of solid ice spheres whose effective diameters are determined by the ratio of the volume-to-surface-area. This greatly simplifies the determination of the refractive (dielectric) properties of the hydrometeors. G-W demonstrated that equivalent spheres can adequately describe the transmittance, and reflectance of diffuse infrared radiation through randomly oriented prisms. Moreover, [6] showed that the equivalent sphere approach accounts for scattering from needles and plates. It is noteworthy that such effective diameters are mainly determined by the small dimensions i.e. the thickness of large disks or the diameters of long cylinders Eq.3. in [5]. rather than the maximum dimensions that are frequently measured, [7].

The size distribution of the equivalent spheres used in this study was assumed to have a distribution function $N(D_{eff}) = N_o\ D_{eff}\ \exp(-D_{eff}/\langle D_{eff}\rangle)$ where $\langle D_{eff}\rangle$ is the mean equivalent size. Once the G-W size distribution was specified, the effective diameter, $\langle D_{eff} \rangle$ was determined by employing attenuation measurements obtained from other snow events ([8] and [9]) to infer the attenuation coefficient per mass (and hence $\langle D_{eff}\rangle$) of snow (Fig.3).

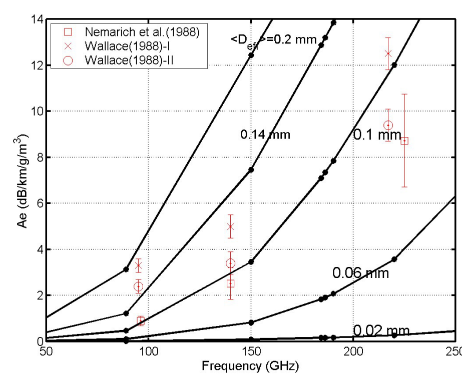


Fig.3 Comparison between the measured attenuation per unit mass (red lines) and the attenuation per unit mass derived from Mie theory using G-W equivalent spheres.

This study assumed snow particles to have a fixed $\langle D_{eff}\rangle$ = 0.1 mm below heights of 500m and $\langle D_{eff}\rangle$ = 0.06mm from z = 500 m to the cloud top.

Fig. 3 displays the curves generated by Mie theory for the 0.1mm and 0.06 mm values of $\langle D_{eff}\rangle$, $\langle D_{eff}\rangle$ = 0.1 mm below 500 m provides a good match the ground-based observations of [8] and [9], while the $\langle D_{eff}\rangle$ = 0.06 mm above 500 m yielded brightness temperatures that best matched the AMSU-B observations. In fact, it is expected that the AMSU-B channels will be more sensitive to the higher altitude (smaller) particles. This is consistent with the previous studies that showed that the crystal habit varied with height and that the large dimension diminished with height [10].

3.3 Snowfall Retrieval

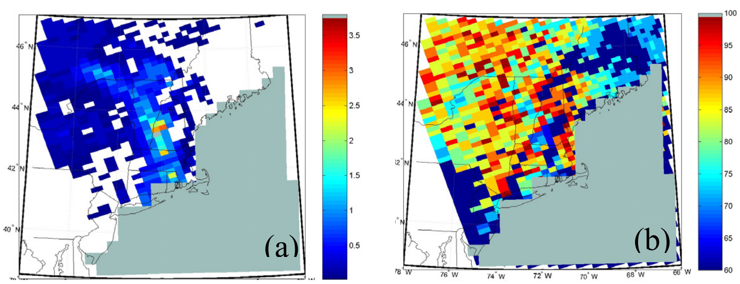
The parameters **r**, **M** and **f** were found by an optimization that sought the minimum of:

$$\Psi(\mathbf{r}, \mathbf{M}, \mathbf{f}) = \Sigma\ [Tb_i - Tb_i^o]^2 = \text{minimum} \qquad (1)$$

where Tb_i and Tb_i^o are the computed and observed brightness temperatures respectively, and the summation is over the five AMSU-B frequency channels. When additional information about the snow or other aspects of the storm conditions become available, these can be included in Eq.(1) to further constrain the optimization.

4. Retrieval Results

Brightness temperature errors that contributed to the $\Psi(\mathbf{r},\mathbf{M},\mathbf{f})$ residuals are within approximately $\pm$ 5 K over most pixels at all of the AMSU-B frequencies. Fig. 4a shows the retrieved snowfall mass density at 20 m. It is evident that the spatial distribution of the snowfall mass is qualitatively similar to the radar reflectivity displayed in Fig. 1.



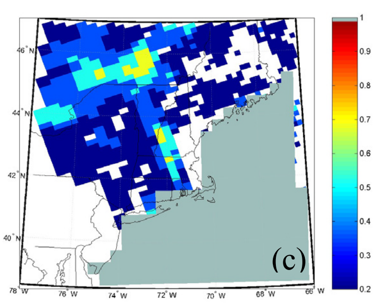


Fig.4 The distribution of retrieved (a) snow mass at 20 m altitude, (b) relative humidity at 1km and (c) fractional snow coverage

Fig. 4(b) shows the retrieved relative humidity distribution at 1 km altitude. The retrieved snow mass and relative humidity distributions are somewhat noisy. If more information were known about the snow profile (such as through vertical radar profiles and in-situ measurements) it is expected that these variations would be reduced. Figure 4(c) shows the distribution of the parameter **f**, the fraction of snow cover on the ground within the AMSU-B field of view. Water in the St. Lawrence basin may have skewed the high snow cover fractions in the Montreal, Quebec, and St. Lawrence river regions because the water surfaces have a lower emissivity. The retrieval algorithm compensated for these lower emissivities (that produce cooler Tb) by increasing the snow fraction.

5. Validation and Discussion

Fig. 5 presents the NWS radar observed dBZ_{eff} shown in Fig.1 as a function of log(R) derived from this pixel matching technique for the retrieval results reported in Fig. 4. The comparison of the retrieved relationship to the previously published relationships is good. While this is not a rigorous validation of the retrieval results, it does show that this physical model enables retrievals to fall within the bounds of existing measured and empirical relationships.

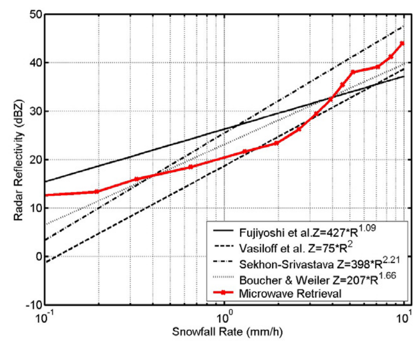


Fig. 5 Measured NWS radar reflectivity, Z, versus melted snowfall rate, R (mm/h). Blacklines show Z-R relations for snowfall shown in other studies.

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